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The Role of Interannual Climate Variability in Controlling Solifluction Processes, Endalen, Svalbard

Charles Harris,[1] Martina Kern-Luetschg,[1] Hanne H. Christiansen[2] and Fraser Smith[3]*

[1] School of Earth and Ocean Sciences, Cardiff University, Cardiff, UK
[2] Geology Department, The University Centre in Svalbard, Longyearbyen, Norway
[3] School of Engineering, University of Dundee, Dundee, UK

ABSTRACT

A continuous record is presented of active layer processes at Endalen, Svalbard, over the period 2005–08. The monitored slope has a gradient of around 7° and in 2005, active layer depth was 94 cm, but this increased by around 14 cm over the next three years. The presence of an ice-rich transient layer proved highly significant in determining the timing and profiles of solifluction movement. Frost heaving was 4.2 cm in 2005–06, 6.6 cm in 2006–07 and 3.2 cm in 2007–08, but thaw settlement exceeded frost heave in each year, giving a net total ground surface lowering of 6.2 cm. In winter, segregation ice was concentrated within the upper and lower active layer, leaving the central parts ice-poor. During the summers of 2006 and 2008, thawing of the transient layer was associated with artesian pore pressures at 90 cm depth and basal soil shearing, but in 2007, when the thaw front failed to reach the ice rich basal zone, pore pressures during thaw were sub-hydrostatic and no basal shearing was observed. Solifluction shear strain during thaw settlement resulted in downslope surface displacements of 2.3 cm in 2005–06, 1.2 cm in 2006–07 and 1 cm in 2007–08. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: Solifluction; active layer; temperatures; frost heave; pore pressures

INTRODUCTION

In this paper, we report results of a field experiment to investigate the response of solifluction processes to natural climatic variability on a high-arctic, low-gradient slope, underlain by continuous permafrost, in Endalen, Svalbard. Field investigations in permafrost regions by Mackay (1981), Lewkowicz and Clarks (1998), Matsuoka and Hirakawa (2000) and others have shown that downslope active-layer displacements due to solifluction occur in late summer when thawing penetrates to an ice-rich 'transient layer' (Schur *et al.*, 2005; Shiklomanov and Nelson, 2007) at the active layer-permafrost interface, causing increased thaw settlement and associated shear deformation within the basal zone. At this time, the active layer moves en masse downslope over the basal deforming layer. Mackay (1981) termed this type of solifluction 'plug-like flow'. In Svalbard, field monitoring by Matsuoka and Hirakawa (2000) at Kapp Linné showed that the presence of non-frost-susceptible marine sands beneath a solifluction sheet resulted in the absence of an ice-rich basal layer. Here, seasonal active-layer thawing caused solifluction in the upper 10–50 cm only, where segregation ice was concentrated, and no soil deformation was observed at depth. In contrast, at a site in Adventdalen, the presence of a transient layer led to solifluction displacements mainly in late summer when this ice-rich zone at the base of the active layer thawed.

Laboratory physical modelling of solifluction processes (combined frost creep and gelifluction), both at full-scale (e.g. Harris *et al.*, 2008a, 2008b) and reduced scale, (e.g. Harris *et al.*, 2003, 2008c; Kern-Luetschg *et al.*, 2008) has indicated that gelifluction occurs as a result of elasto-plastic deformation of saturated soils during thaw consolidation, deformation resulting from the loss of soil frictional strength arising from low effective stresses. A direct relationship between thaw settlement and soil shear strain was observed, with strain concentrated where the active layer was most ice-rich and therefore subject to greatest thaw consolidation. Recent field studies on seasonally frozen solifluction slopes by Harris *et al.* (2008d) and Matsumoto *et al.* (2010) have supported these laboratory experimental results, with solifluction soils observed to deform most where thaw settlements were greatest.

* Correspondence to: Charles Harris, School of Earth and Ocean Sciences, Cardiff University, Cardiff CF10 3YE, UK.
E-mail: harrisc@cardiff.ac.uk

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Rising air temperatures in many arctic regions, including Svalbard, associated with an increase in the frequency of warm years, are in the future likely to cause deeper active layers with thaw advancing into ice-rich frozen ground that has not thawed for many decades, centuries or even millennia (Isaksen *et al.*, 2007; Christiansen and Humlum, 2008; Harris *et al.*, 2009). In consequence, it is anticipated that there will be a marked increase in both the rates of solifluction and the volume of annual sediment transport (Matsuoka, 2001; Åkerman, 2005). Here, we present data on ground and air temperatures, snow depth, frost heave, thaw settlement, porewater pressures and downslope soil movement over the three-year period 2005–08. The field experiment was initiated in Endalen, Svalbard in August 2005 and seeks to measure the response of the active layer to year-on-year climatic variability, and hence to provide a clearer understanding of the likely impacts of longer term and larger scale changes in climate. The first three years of measurements reported here represent the initial phase of a planned long-term solifluction monitoring programme. Comparisons between the three annual cycles of ground freezing and ground thawing discussed in this paper (years 2005–06, 2006–07 and 2007–08) relate to the period 1 October to 30 September inclusive.

SITE DESCRIPTION

The solifluction slope investigated here is located at an elevation of around 75 m a.s.l. on the east-facing valley side of Endalen in Svalbard (78°11´N, 15°44´E), a tributary valley of Adventdalen, some 4 km southeast of Longyearbyen (Figure 1a). The mean annual air temperature at Svalbard Airport, Longyearbyen (approximately 8 km from the study site) is −6.8°C (1961–90), and mean annual precipitation is 190 mm. However, the last decade, including the period of field monitoring reported here, has been characterised by significantly higher temperatures than the long-term average (Isaksen *et al.*, 2007; Harris *et al.*, 2009; see Figure 7).

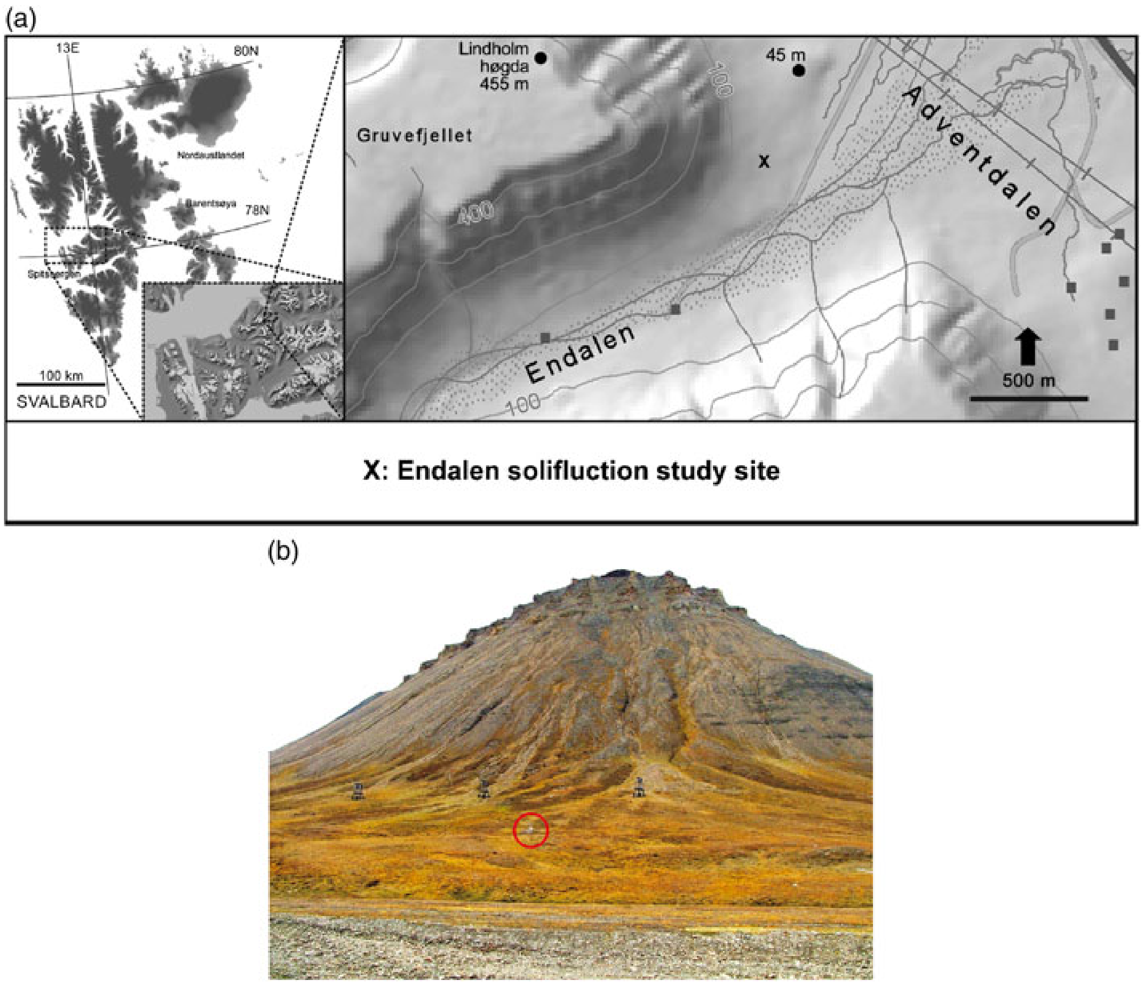

Figure 1 (a) Location of the Endalen solifluction study site. (b) Site and situation of the monitoring station in Endalen showing a steeper upper slope and lower angle solifluction sheet forming the footslope zone. The photograph was taken looking northwest from the valley-bottom braided riverbed. The wooden pylons at the top of the footslope zone are coalmining relicts in Endalen. The monitoring station is circled.

Endalen is formed in Early Cretaceous sandstones, conglomerates, clay ironstones, shales and coal of the Carolinefjellet Formation (Harland, 1997). Dips are low and to the south, and typical valley-side profiles comprise a plateau crest below which is a scree-covered upper slope of between 30° and 40° with frequent bedrock outcrops. This steeper upper slope gives way below to a gently concave solifluction sheet that extends to the braided river system in the valley bottom. The field monitoring site is located on this solifluction sheet, has a surface gradient of approximately 7° (Figure 1b) and an active-layer thickness of around 1 m. The active-layer soil is a frost-susceptible sandy silt diamicton containing numerous sandstone clasts up to boulder size, and occasional organic-rich lenses. Grain size distribution of the fraction finer than 20 mm is shown in Figure 2.

Geotechnical properties reflect the soil granulometry (Table 1), with low values of plastic and liquid limits and low plasticity meaning that soil consistency is sensitive to moisture changes. Such values are typical of many arctic and alpine solifluction slopes where clay contents are low (Harris, 1981).

Drilling to around 2.5-m depth in August 2005 revealed ice contents below around 90-cm depth averaging around 45 per cent by volume (Figure 3a), the ice being in the form of irregular masses and lenses up to 20 mm in thickness (Figure 3b). The ice-rich frozen ground below 90 cm likely corresponds with an ice-rich transient layer (Shur *et al.*, 2005) that extends into the upper permafrost. A high-resolution resistivity tomography survey in August 2006 by Dr L. Kristiansen along a 30-m slope transect adjacent to the monitoring station showed a uniform thaw depth of around 1 m and highly resistive (modelled resistivity > 4000 Ω m), ice-rich near-surface permafrost extending the length of the survey line, suggesting that the ice-rich transient layer is spatially extensive in this location.

INSTRUMENTATION

The site was instrumented (Figure 4) in August 2005 (see Harris *et al.*, 2007, for details). Ground surface movements were monitored using a linked pair of waterproof longstroke (200-mm range) captive-guided armature linear variable differential transformers (LVDTs) supplied by RDP Electronics Ltd, UK. The LVDTs formed a fixed base triangle mounted via end bearings on a tubular steel scaffolding bar set parallel to the ground surface and 0.5 m above it, the bar being supported by a tubular steel frame with similar tubular steel legs frozen into the permafrost (Figures 4a and 5). The LVDT triangle apex was formed by joining the two LVDTs via ring bearings to an 8-cm square stainless steel footplate embedded in the ground surface (Figure 4b). Frost heave, thaw settlement and downslope displacements of the soil surface were registered by movements of the footplate that caused changes in the length of the two LVDTs. Movements were resolved as orthogonal vectors perpendicular and parallel to the soil surface to an estimated accuracy of ± 1.5 mm over the operating temperature range (see Harris *et al.*, 2007, for details).

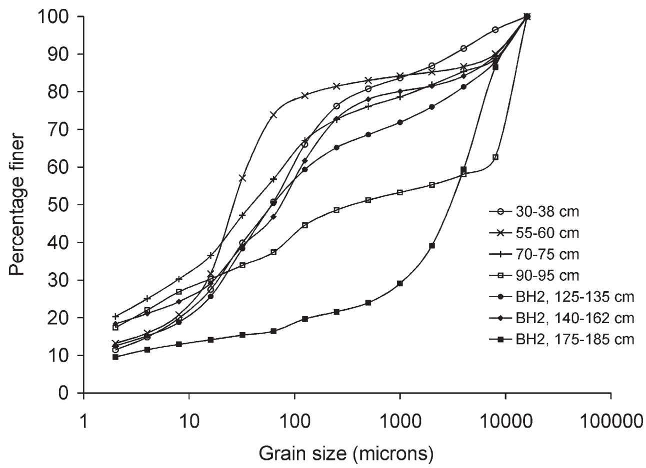

Figure 2 Grain size distribution in unfrozen samples from the instrumentation pit and frozen samples from borehole 2 (BH2).

Table 1 Geotechnical soil properties of the Endalen active layer.

Soil	% sand	% silt	% clay	PL (%)	LL (%)	PI (%)	Ø (°)
Endalen	26–63	20–60	11–20	26	33	7	26

Granulometry and index properties are based on six samples from 30–90 cm depth, internal angle of friction on three determinations on samples from 50–80 cm depth. PL = Plastic limit; LL = liquid limit; PI = plasticity index; Ø = internal angle of friction.

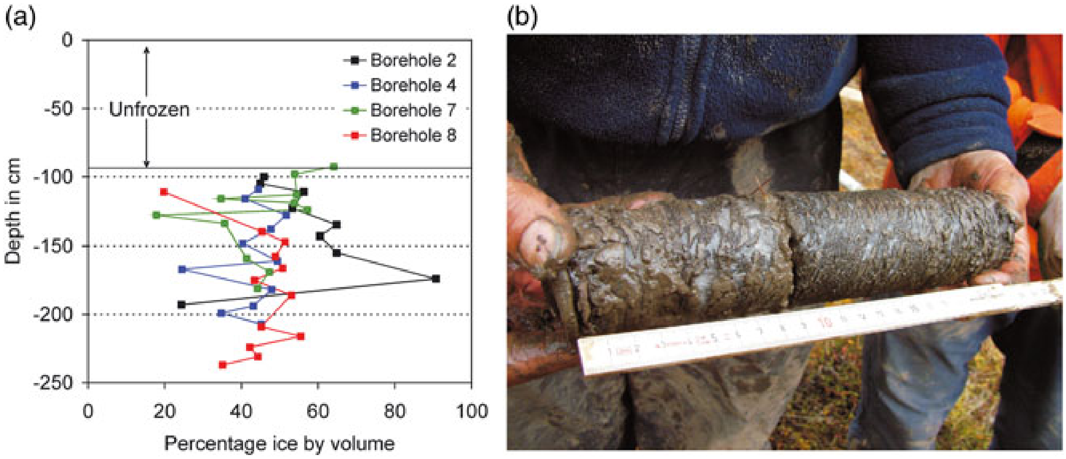

Figure 3 (a) Per cent ice volume below the thaw front, 15 August 2005, calculated from weighed and dried samples. Samples of frozen soil were obtained by motorised hand drilling of boreholes used for the installation of the recording instruments. Thaw depth was around 90 cm at the time of drilling. (b) Example of a recovered core from the ice-rich transition zone and upper part of the permafrost, borehole 2.

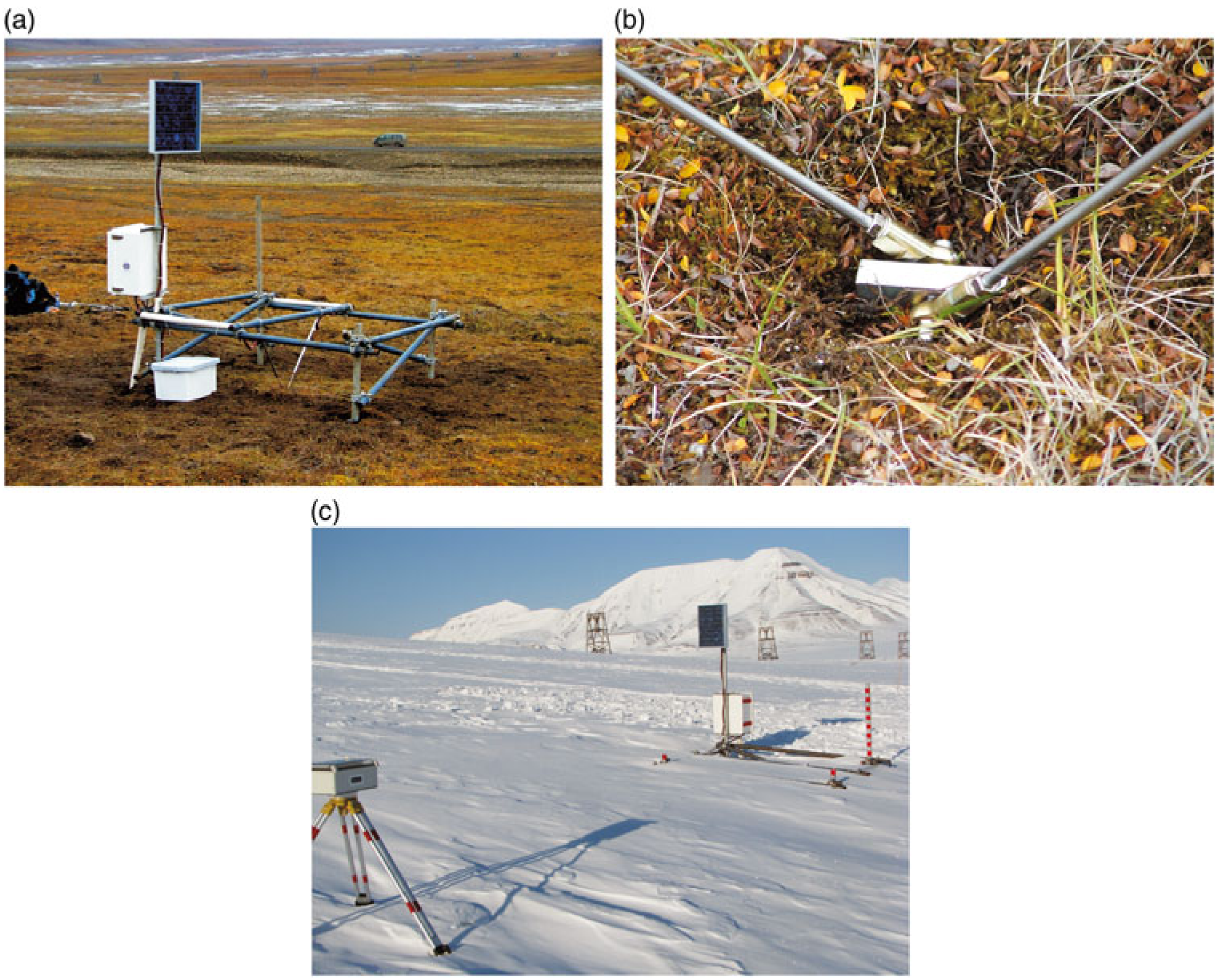

Figure 4 (a) Monitoring station showing the supporting frame, solar panel, the linear variable differential transformer (LVDT) triangle, the battery container (white box on the ground) and the logger box attached to the solar panel pole. (b) Footplate embedded in the ground surface forming the apex of the LVDT triangle. (c) Station photographed 4 April 2008 showing the snow camera on the left and graduated poles against which snow depths were measured (two short poles near side of the station just protruding from the snow, longer pole on far right-hand side of the station). Photograph by A. G. Lewkowicz.

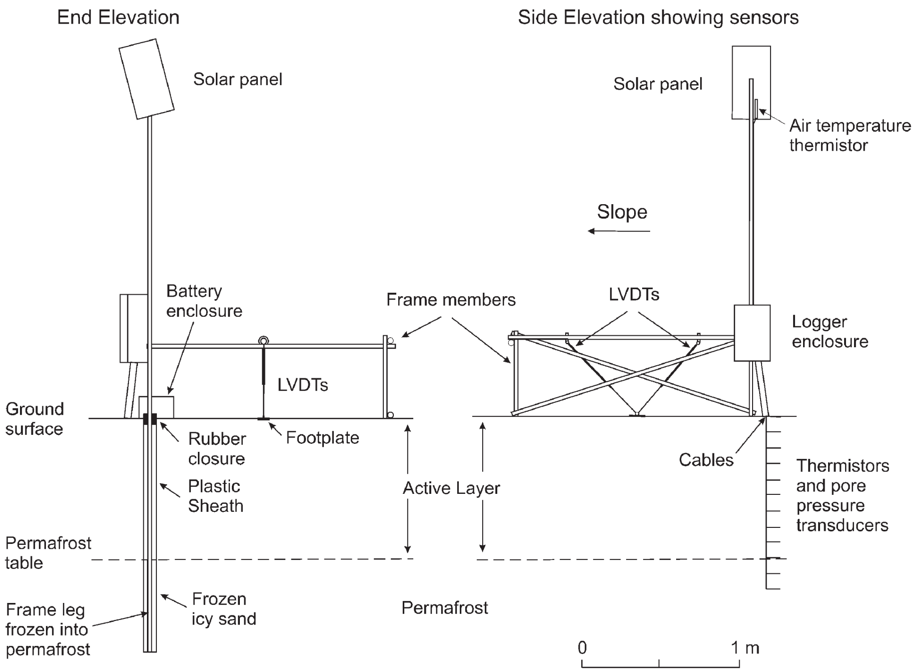

Figure 5 End and side elevations of the Endalen monitoring station. Note that spacing and depth of the thermistors and pore pressure transducers are shown diagrammatically here. Thermistor depths were 0 cm, 15 cm, 30 cm, then at 10-cm intervals to 100 cm, with the deepest at 120 cm, while pore pressure transducers were installed at 30 cm, 60 cm, 70 cm, 80 cm and 90 cm. LVDTs = Linear variable differential transformers.

Temperature measurement was achieved via vertical arrays of stainless steel thermistor probes supplied by Campbell Scientific Ltd, UK. Thermistors were placed at the surface, and at depths of 15 cm, 30 cm and subsequently at 10-cm intervals to 90 cm (Figure 5). Drilling into the upper permafrost allowed further thermistors to be installed at 100-cm and 120-cm depths. Air temperature thermistors were shielded by rigid 2-cm diameter white plastic tubing and mounted on solar panel poles at heights of 1 m and 2 m. Thermistor interchangeability error was ± 0.18°C and bridge resistor error ± 0.13°C.

In addition, a rugged automatic digital camera (see Christiansen, 2001, 2005) enclosed in a weatherproof case and mounted on a firmly anchored tripod was installed to provide high-resolution colour images of the site. The camera was programmed to take daily images at mid-day and snow depth was estimated against graduated poles at the corners of the station (Figure 4c).

Soil pore pressures were measured using Druck UK PDCR 81 miniature pore pressure transducers filled with silicon oil to allow operation above and below 0°C. These were installed adjacent to the buried thermistor array at depths of 30 cm, 60 cm, 70 cm, 80 cm and 90 cm. The transducers had a range of 350 mb, and a combined non-linearity and hysteresis of ± 0.2 per cent.

All data except for the snow camera digital images were recorded at hourly intervals via a Campbell Scientific CR23X logger with a 16/32 channel multiplexer and powered by a 12 V heavy-duty car battery charged with an 18 W solar panel (Figure 4a). All cabling between sensors and logger was either buried or encased in plastic tubing to protect it from animal damage. The battery voltage supply ranged from more than 14 V in summer to 11.5 V in late winter.

RESULTS

In the following sections, all instrument depths were measured when the active layer was unfrozen. When frozen, the presence of segregation ice increased the thickness of the soil column and therefore the vertical spacing of the sensors.

Air Temperatures and Snow Cover

Ground and air temperatures for the period September 2005 to November 2008 are shown in Figure 6, and snow depths measured at the monitoring station are shown in Figure 7. In April 2006, above average air temperatures contributed to clearance of the snow (Figure 7) and initiation of ground thawing by early May, approximately one month earlier than in the succeeding two years.

The accumulated freezing-degree days (FDDs) for air temperature measured 2 m above the ground surface in 2005–06 (1 October to 30 September inclusive, Figure 8) reveal an annual accumulated total of 775 FDDs, compared with 1196 FDDs for 2006–07 and 1206 FDDs for 2007–08,

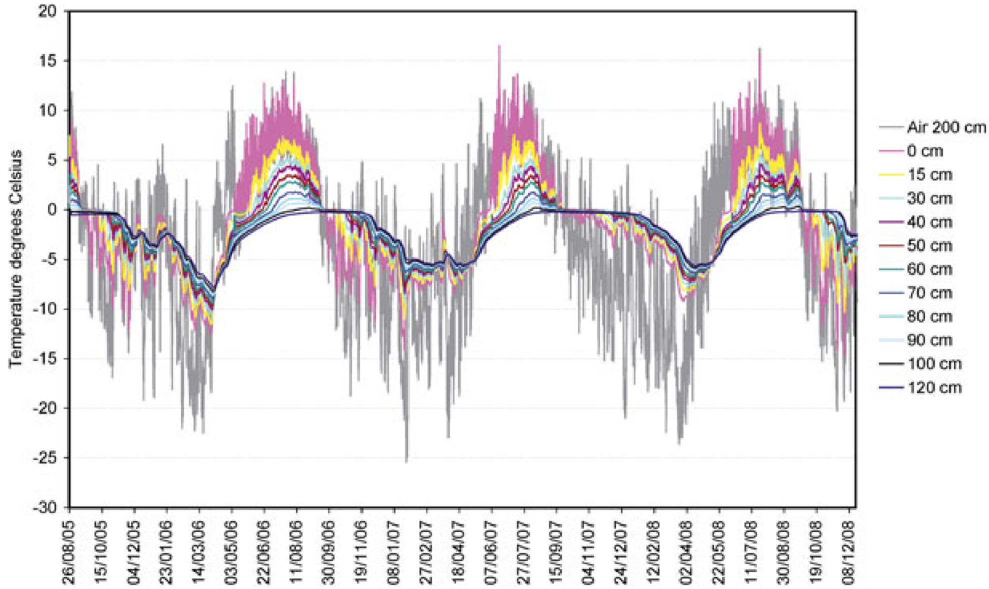

Figure 6 Air and ground temperatures in Endalen from 1 October 2005 to 30 September 2008.

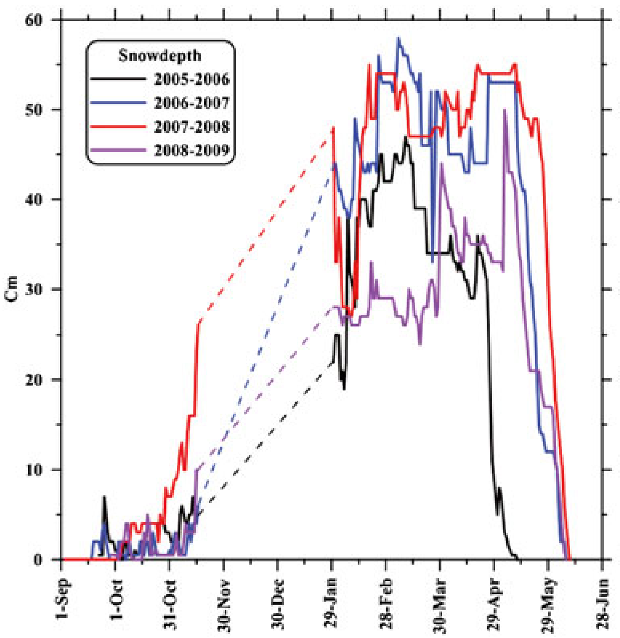

Figure 7 Snow depth at Endalen estimated from daily snow camera photographs.

emphasising the positive thermal anomaly in air temperatures during this first year of measurement. The significance of snow depth and duration on the ground surface thermal regime is illustrated by comparing the accumulated FDDs for air temperature 2 m above the ground and that for the ground surface temperature (Figure 8). Winter ground surface temperatures were clearly significantly higher than air temperatures, especially in 2007–08 (see Figure 6), when the snow thickness in early winter greatly exceeded the two previous years (Figure 7). The total FDDs at the ground surface in 2007–08 was only 263, compared with 553 in 2005–06 and 831 in 2006–07, indicating less heat conduction from the ground to the air in 2007–08 despite higher total air temperature FDDs than in the previous two years.

Slower ground cooling in autumn 2007 beneath a thicker snow cover is well illustrated in Figure 9, with ground temperatures in the lower active layer not falling below −0.2 °C until mid-December 2007, compared with mid-November in both 2006 and 2008. Snow depths varied significantly between the years both in terms of timing and thickness. The maximum snow depth was around 55 cm in 2006–07 and 2007–08, but only 45 cm in 2005–06, the maxima being recorded in the period February to May.

Active-layer Thermal Regime

Two aspects of the thermal regime are particularly important; firstly, autumn freeze-back during which ice segregation causes frost heaving in the active layer, and secondly, the rate and depth of summer thaw penetration, with its associated thaw settlement and solifluction movements.

Active-layer Freezing.

The ground temperature record (Figure 6) clearly shows a marked ‘zero curtain’ effect during autumn ground freezing, when active-layer temperatures remained between 0°C and −0.2°C, and ice segregation took place. Plotting penetration of the 0°C isotherm in spring and summer defines when the soil became completely unfrozen (temperatures above 0°C), but in autumn, the zero-curtain effect resulted in soil freezing and ice segregation continuing for several weeks after penetration of the 0°C isotherm, when active-layer temperatures were between 0°C and around −0.2°C (Figure 9).

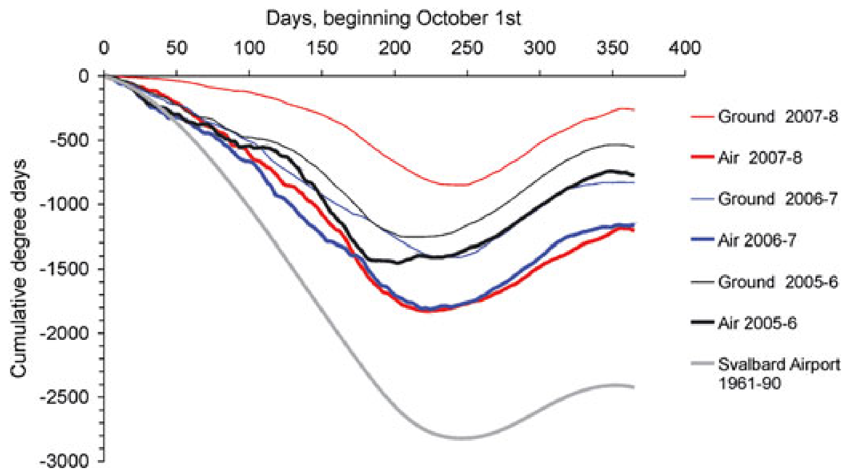

Figure 8 Cumulative freezing-degree-day air and ground surface temperatures for the three years from 1 October 2005 to 30 September 2008. Air = Air temperature 2 m above the ground surface; Ground = ground surface temperature. Data for Svalbard Airport were supplied by Dr Ketil Isaksen, Norwegian Meteorological Institute, Oslo.

During autumn 2006, the active layer was approximately isothermal (between 0°C and −0.2°C) to a depth of 100 cm by late September and the upper boundary of this isothermal zone (the −0.2°C isotherm) moved downwards from the surface, reaching the base of the active layer by 12 November (Figure 9a). As indicated earlier, active-layer freezing in 2007 was much slower than in the previous year, reflecting the insulating effect of the early snow in 2007. The ground surface temperature reached 0°C on 12 September 2007 and the active layer became approximately isothermal (temperature between 0°C and −0.2°C) by 25 September. The upper boundary of the zero-curtain zone migrated slowly downwards, not reaching 90 cm until 17 December (Figure 9b). Heat conduction into the underlying permafrost also caused cooling of the basal active layer below 90-cm depth over this period. In autumn 2008, ground temperatures fell to below 0°C at the surface on 25 September, the active layer rapidly becoming isothermal. The −0.2°C isotherm then progressed downwards and reached the permafrost table by mid-November (Figure 9c).

Active-layer Thawing.

The maximum depths of thaw penetration, derived from thermal gradients in early September, were estimated to the nearest whole centimetre. Maximum thaw penetration was around 94 cm in summer 2005, when instrumentation was installed, 106 cm in 2006, 100 cm in 2007 and close to 110 cm in 2008. Note, however, that active-layer thickening associated with overall lowering of the permafrost table between summer 2005 and summer 2008 was significantly less owing to thaw settlement at the ground surface in summer (see below).

Rates of thawing are largely a function of the thermal gradient (controlling heat flux to the thaw front) and soil ice content (controlling latent heat flux from the thaw front). Thaw penetration to a depth of 90 cm in 2006 took until around 21 July, averaging 1.45 cm/day but the rate slowed markedly beyond this depth to around 0.3 cm/day, reflecting the high ice content and therefore high latent heat capacity within the transient zone (see Figure 3b). In 2007, thaw penetration averaged 1.64 cm/day to a depth of 100 cm, which was reached by early August, but little further thaw penetration was observed. In 2008, thawing to a depth of 100 cm averaged 1.92 cm/day, again reached by early August and thereafter the thaw penetration rate dropped to around 0.16 cm/day as the thaw front again advanced through ice-rich soil. The thermal gradient in the zone between 70 and 100 cm depth in late August 2007 was only −0.015°C/cm, compared to −0.035°C/cm in 2006 and −0.031°C /cm in 2008, suggesting a rate of downward heat conduction in 2007 approximately half that in the preceding and succeeding years assuming a similar thermal conductivity in the unfrozen soil. It may be noted that the accumulated ground surface FDDs in 2006–07 significantly exceeded the other two years (Figure 8), emphasising the cooler conditions through that year.

Pore Pressures due to Ice and Water

The Druck miniature pore pressure transducers utilised here are designed to measure porewater pressures, and were calibrated against known heads of water. However, when these transducers were in contact with developing soil ice, large increases in pressure were recorded, sometimes beyond the measurement scale set for the Campbell logger. Where thermal data indicated freezing temperatures but no ice pressures were recorded by the pore pressure transducers, it may be assumed that the soil was ice-poor in the immediate vicinity of the transducer tip.

Ice Pressures.

Very high ice pressures (>50 kPa) were recorded at 80 cm and 90 cm depths in the winters of 2005–06 and 2007–08, but not during 2006–07, suggesting an absence of significant

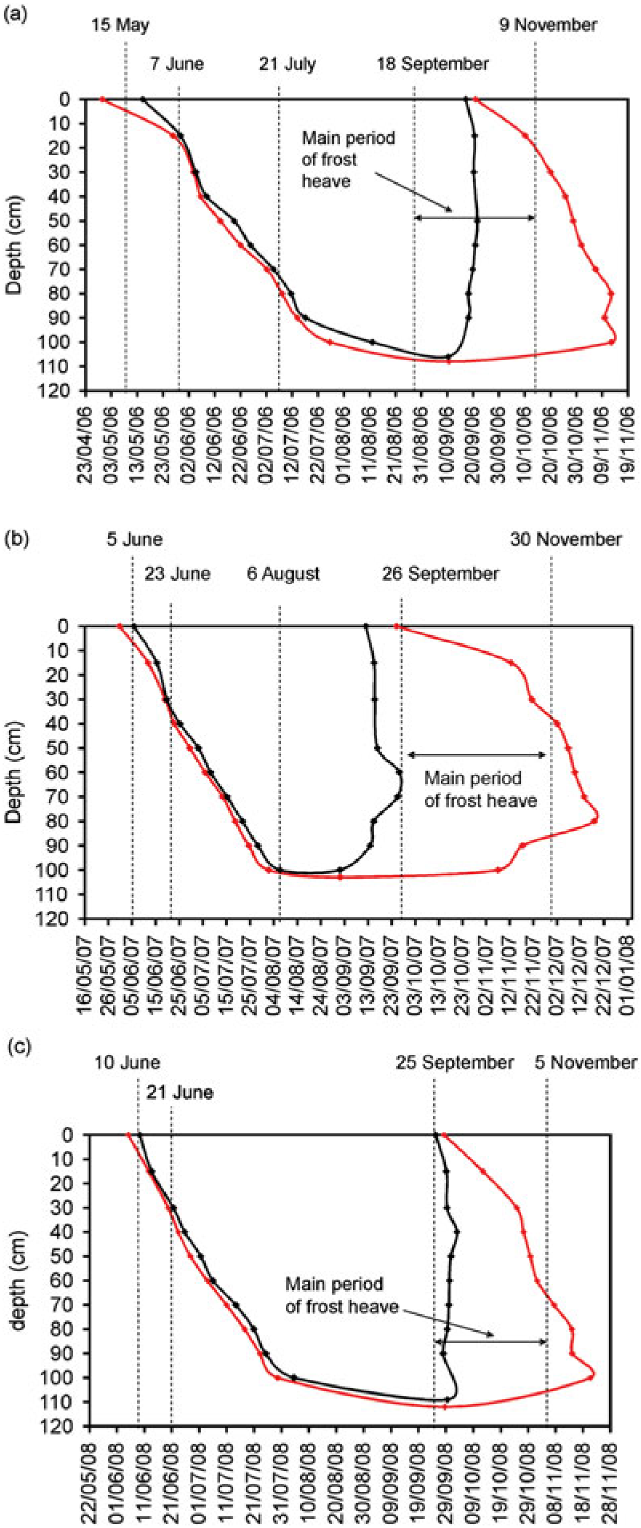

Figure 9 Penetration of the 0°C isotherm (black line) and −0.2°C isotherm (red line): (a) 2005–06; (b) 2006–07; (c) 2007–08.

segregation ice at depth in 2006–07. This presumably reflected a lack of soil water above the permafrost table when freezing at depth took place in the autumn of 2006, and is supported by strongly negative pore pressures recorded there at this time (Figure 10). It is noteworthy that the −0.2°C isotherm penetrated rapidly between around 80-cm depth and the base of the active layer in autumn 2006, suggesting little ice segregation and the release of latent heat at these depths. Significant ice pressures were, however, recorded at 70 cm depth in autumn 2006, suggesting that ice segregation occurred at this depth, and it may be noted that frost heaving continued until 9 November 2006 (Figure 9a), which includes the period when soil at 70 cm became frozen. As indicated above, during the 2007 freeze-up, ice pressures were again recorded at 80 cm and 90 cm but not at 70 cm. Soil freezing at 80 cm and 90 cm in autumn 2007 was associated with an upwards advance of the −0.2°C isotherm due to heat conduction downwards into the permafrost below (Figure 9b), and frost heaving of the ground surface during this time suggests the occurrence of ice segregation in these basal layers.

Mackay (1983) highlighted the potential for downwards migration of meltwater into still-frozen soil during active-layer thawing. Refreezing of this meltwater would increase the ice content at depth and may cause renewed frost heave (termed summer heave by Mackay, 1983). These processes apparently occurred immediately following the initiation of spring ground surface thawing in Endalen, and caused a rapid rise in pore pressures in still-frozen soil at 30-cm and 60-cm depths (labelled (a) in Figure 10). It should be noted that no excess pore pressures due to ice formation were recorded at these depths during autumn freeze-up in any of the monitored years. Refreezing of percolating meltwater released latent heat, and as a result, a sharp rise in temperatures in the upper active layer (Figure 11) was also observed. In each of the three years, this temperature rise propagated downwards from 30 cm to close to the base of the active layer over a period of between 11 h (2006) to 22 h (2007), with marked attenuation below 60 cm. It appears, therefore, that refreezing of downwards percolating meltwater into still-frozen but relatively ice-poor central parts of the active layer increased the ice contents, most markedly between 30 cm and 60 cm depths. Corresponding frost heave at the ground surface was not observed however, possibly because the frozen soil was initially dry and much of the newly formed ice was pore ice rather than segregation ice.

Porewater Pressures.

Pore pressures rose immediately following soil thawing at a given depth (Figure 10), with recorded porewater pressures increasing with depth. Porewater pressures were high in 2005–06 and 2007–08, but much lower in 2006–07. The initiation of soil thawing at each monitored depth was marked by a short-lived spike, possibly reflecting influx of meltwater from above into a partially thawed soil structure (see, for instance the period between 2 June and 12 July 2006, Figure 10). The succeeding period of thaw settlement was associated with more uniform, relatively high pore pressures that did not decline until towards the end of the

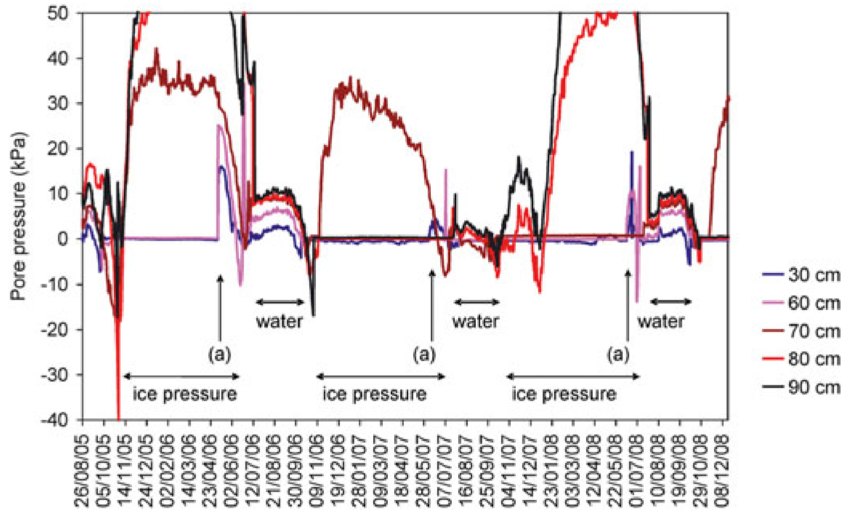

Figure 10 Pore pressures August 2005 to December 2008. Sharp rises in ice pressure in the upper active layer during late-spring 2006, 2007 and 2008 indicate refreezing of meltwater percolating downwards into still-frozen soil and are labelled (a) in the diagram.

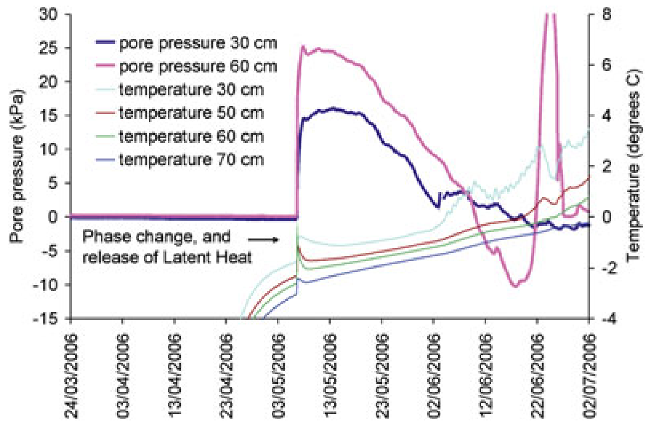

Figure 11 Pore pressures at 30-cm and 60-cm depths and corresponding ground temperatures during spring 2006.

summer period. Maximum recorded values at 90-cm depth were 11.4 kPa in August 2006, 10.3 kPa in August 2008, but only 3.9 kPa in August 2007. This was equivalent to a pressure head at 90-cm depth of 116 cm water in 2006 and 105 cm in 2008, but only some 40 cm in 2007. Figure 12 shows porewater pressure distribution with depth when basal pore pressures were highest. A basal zone with artesian pore pressures is indicated in summers 2006 and 2008, but not in 2007. It should be noted that the thaw plane reached a depth of 106 cm in summer 2006, penetrating the ice-rich frozen ground observed at this site in boreholes (Figure 3a,b) and indicated by the resistivity survey. The latter suggested that ice-rich frozen ground is spatially continuous in the upper permafrost immediately below the active layer over at least a 30-m long transect of this slope. In summer 2007, active-layer depth was only 100 cm (6 cm less than in the previous year) and thawing did not reach the ice-rich zone. In summer 2008, the thaw depth exceeded that of 2006, so that once again the thaw front intercepted

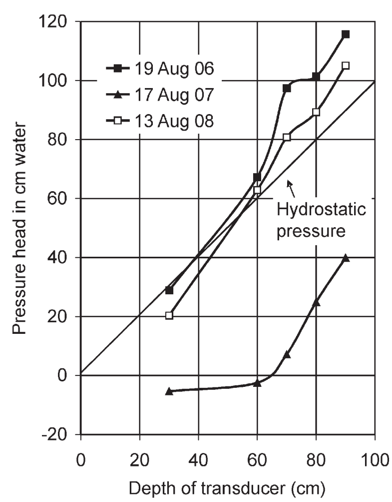

Figure 12 Measured head of water plotted against transducer depth at the time of maximum basal pressures. Note the hydrostatic pressure line.

the ice-rich transient zone and meltwater from segregation ice was once again released into the base of the active layer, generating the observed high pore pressures. See page of meltwater from upslope of the site, across the top of the permafrost, may also have contributed to the elevated pore pressures observed in 2006 and 2008.

Ground Surface Frost Heave, Thaw Settlement and Downslope Displacements

By resolving changes in the length of the LVDTs and using trigonometry of the LVDT triangle in the vertical plane parallel to the fall line (direction of maximum slope), movement of the footplate perpendicular to and parallel to the ground surface (heave/settlement and downslope displacements, respectively) was determined (Figure 13) (see Harris *et al.*, 2007, for details). Combining these orthogonal footplate displacements (parallel and perpendicular to the ground surface) generates the movement vector of the ground surface as recorded by the embedded footplate (Figure 14).

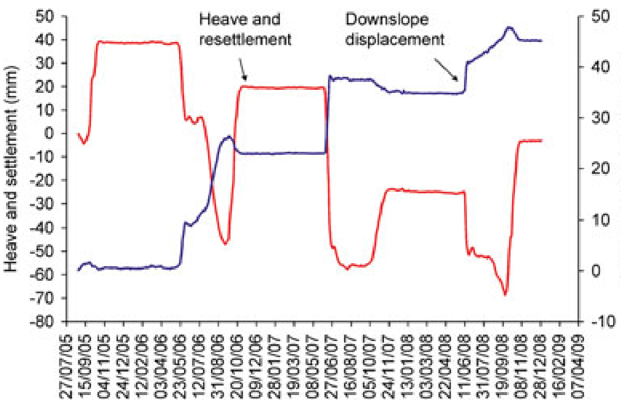

Figure 13 Ground surface heave and resettlement (red) and downslope displacement (blue) as recorded by movements of the linear variable differential transformer footplate.

Considerable variation in winter frost heave (which may be assumed to reflect active-layer ice content) and subsequent summer thaw settlement (which results from thawing active-layer segregation ice, plus in some years, thawing of soil ice in the transient zone) was observed over the three years reported here (Table 2). Thaw settlement consistently exceeded frost heave with the result that late-summer ground surface elevation was reduced by some 62 mm between 2005 and 2008 at the monitoring station. This net fall in surface elevation over the three years reflects the loss of a similar thickness of ground ice as the permafrost table was lowered through this period.

Temporal changes in the rate of ground surface thaw settlement showed similar patterns in the summers 2006 and 2008, but there was a marked contrast in 2007. In 2006, settlement of 32 mm was recorded over the first 23 days of ground thawing, followed by a period with little net settlement between 7 June and 21 July (44 days). Renewed thaw settlement then began and continued for 59 days, during which a further 52 mm of surface settlement occurred. In 2008, 25 mm of settlement was recorded between 9 and 21 June (12 days), followed by a period with only 2 mm settlement in 22 days (until 12 August). Finally, between 12 August and 25 September 2008, a further 15 mm surface settlement was recorded as the basal part of the active layer thawed (Figure 13). Reference to the thaw penetration curves of 2006 and 2008, respectively (Figure 9), shows that the periods with only slight surface settlement corresponded with thawing of the layer between around 36 cm and 92 cm in 2006 and between around 30 cm and 100 cm in 2008. Assuming that surface settlements largely reflected thaw consolidation immediately behind the thaw front, this indicates a zone in the middle to lower active layer with little excess ice. In 2007, thaw settlement of some 66 mm was recorded during thawing of the upper 40 cm of the active layer (Figure 13), but subsequent thaw penetration to around 100-cm depth resulted in only a further 10 mm of thaw settlement. Thus, active-layer ice content following the autumn 2006 freeze-up was fairly

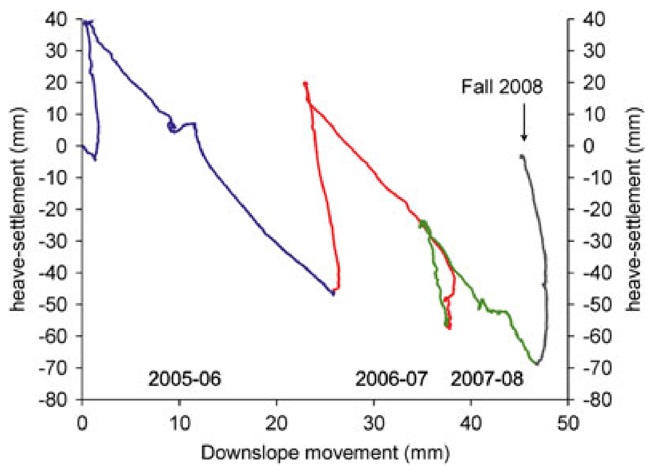

Figure 14 Annual accumulated movement vectors for the ground surface: 2005–06 (blue), 2006–07 (red), 2007–08 (green) plus autumn 2008 (grey).

Table 2 Frost heave, thaw settlement and surface downslope movements measured at the Endalen station.

Autumn	Spring/summer	Frost heave (mm)	Thaw settlement (mm)	Potential frost creep (mm)	Net surface downslope movement (mm)
2005		42			
	2006		84	10	22
2006		66			
	2007		76	9	12
2007		32			
	2008		42	5	10

Note: Potential frost creep is the surface movement that would result from vertical ground surface settlement under gravity during thaw consolidation.

uniform to a depth of around 40 cm, but much less excess ice was present between 40 cm and 100 cm, the maximum depth of thaw penetration.

Downslope Soil Movement

Downslope movement of the ground surface due to solifluction was observed to largely correspond with periods of thaw settlement (Figure 13), and taking account of slight retrograde movements observed during winter freeze-back, the total surface movement in 2006 amounted to 22 mm, compared with 12 mm in 2007 and 10 mm in 2008 (Table 2). It may be assumed that the majority of the thaw consolidation (volume strain causing surface settlement) and associated soil shear strain (causing downslope surface movements) took place immediately behind the thaw front as voids left by melting ice lenses were closed (see Harris *et al.*, 2008c). In the summer thaw periods of 2006 and 2008, downslope movements were recorded as the thaw front migrated from the surface to around 35-cm depth (Figures 13 and 14), followed by little or no downslope movement during thawing of the ice-poor zone below approximately 35 cm and then a final period with renewed surface movements as the thaw front penetrated the ice-rich basal transient layer. In contrast, in summer 2007, downslope movement was only observed during thawing from the surface to slightly less than 40-cm depth, after which movements ceased, and further small surface settlements were associated with slight retrograde movement, probably resulting from drying of the active-layer soil. As noted earlier, the depth of thaw penetration in 2007 was less than in 2006, so the thaw front failed to reach the ice-rich basal transient zone.

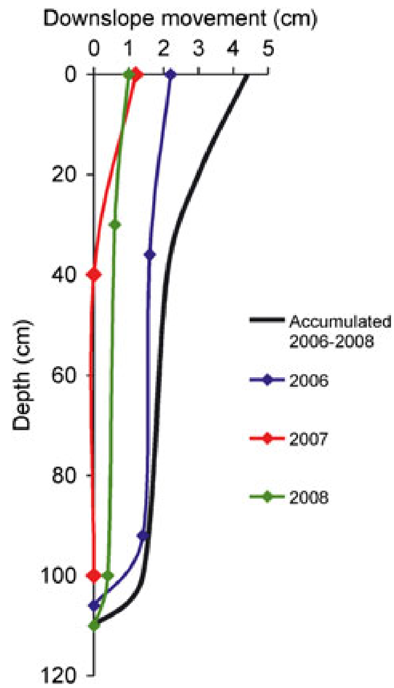

Figure 15 Synthetic profiles of soil movement derived from contemporaneous time series for thaw penetration and downslope surface displacements 2005–06, 2006–07 and 2007–08, together with accumulated total displacement profile over the three years. Profiles were calculated by assuming that thaw settlement and associated soil shearing took place immediately behind the penetrating thaw front. Note the difference in scale between axes.

INTERPRETATION OF RESULTS AND DISCUSSION

Solifluction Deformation Profiles in 2006, 2007 and 2008

The LVDT triangle and its footplate provided real-time information on when surface movements occurred, and thermistors provided synchronous thermal data through the active layer and into the permafrost. By relating the depth of thaw penetration (thermistor data) at the time when surface movement took place (LVDT data), and assuming that soil shear strain (solifluction) occurred immediately behind the thaw front as the soil consolidated, it is possible to construct synthetic profiles of soil deformation for each of the three monitored summer thaw periods (Figure 15). Two distinct patterns may be discerned. Firstly, in 2006 and 2008, when shear strain was concentrated in the uppermost 30 cm and the lowermost 10 cm of the active layer, in the zones where thaw consolidation was greatest; and secondly, in 2007, when significant shear strain and thaw consolidation occurred only in the uppermost 30–40 cm, but not at greater depths. As noted above, thaw penetration in 2007 was less than in 2006 and no basal ice-rich layer was therefore encountered. Thus, melting of segregation ice in the upper 40 cm caused thaw consolidation and solifluction movements in all years, but it was only when thawing penetrated the ice-rich transient layer (2006 and 2008) that significant basal thaw consolidation and basal soil deformation occurred.

Relationship between Thaw Settlement and Solifluction Shear Strain

At Endalen, the active layer in both 2006 and 2008 could be divided into three layers within which shear strains were consistent (near-surface deforming layer, mid-layer with little deformation and basal deforming layer), but in 2007 only two layers were identified (near-surface deforming layer and deeper layer with little deformation). A plot of shear strain due to solifluction within each layer against corresponding normalised axial strain within that layer (thaw settlement within the layer divided by the unfrozen consolidated layer thickness) shows a consistent relationship for all three years of the study (Figure 16). This suggests that high basal shear strains observed in 2006 and 2008 reflected correspondingly high basal thaw settlements rather than any change in process from, for instance, solifluction (i.e. elasto-plastic shear strain; Harris *et al.*, 2008c) to some more rapid shearing process associated with the development of distinct slip surfaces. This observed relationship between normalised axial strain within a thawing soil layer and resulting shear strain within it is in accordance with the results of full-scale laboratory simulation experiments (Harris *et al.*, 2008a) and scaled centrifuge experiments (Kern-Luetschtg *et al.*, 2008), and the gradient of the regression (shear strain per unit of axial strain) is likely to be a measure of the susceptibility of the particular soil in question to solifluction.

Porewater Pressures and Slope Instability

Given the simple geometry of the Endalen study slope, an assessment of the potential for initiation of rapid active-layer detachment landsliding across discrete shear surfaces during active-layer thaw (e.g. Chandler, 1972; Lewkowicz, 1990) may be made using the infinite slope model of Skempton and DeLory (1957) and assuming a planar slip surface parallel to the ground surface. If edge effects are ignored,

$$F_s = \frac{c' + z(\gamma - m\gamma_w)\cos^2\beta\tan\phi'}{z\gamma\sin\beta\cos\beta} \tag{1}$$

where γ is the bulk unit weight of the thawing soil, γ_w is the unit weight of water, z is the depth of the potential slip surface, m is the ratio of the height of the piezometric surface above the slip surface to the vertical depth of the slip surface below the ground surface, β is the slope angle and ϕ' is the effective internal angle of friction of the soil. Assuming soil strength parameters $\phi' = 26°$ and $c' = 0$, and bulk density 2 Mgm^{-2} and using the maximum pore pressures recorded at 90-cm depth (11.4 kPa in 2006), the factor of safety against slope failure was 1.3 and critical pore pressures to initiate failure would have been 13 kPa or 14 per cent higher than those recorded in summer 2006. Thus, the monitored slope is predicted to have remained stable during the period of high basal pore pressures in summer 2006. The critical slope angle for failure at this time was around 9°, compared to the actual gradient of around 7°. Clearly, there is considerable uncertainty in this simple model of potential slope failure, particularly in relation to the effective internal angle of friction and the effective cohesion within a non-uniform soil. The model also ignores edge effects within a potential landslide. Thus, it is likely that the calculated factor of safety is on the low side. However, under a scenario of climate warming, if more extreme summer temperatures were coupled with greater snow depths in winter (both trends tending to warm the upper ground layers and increase the depth of thawing), the resulting thicker active layers and higher summer basal porewater pressures might lead to an increased risk of shallow active-layer detachment

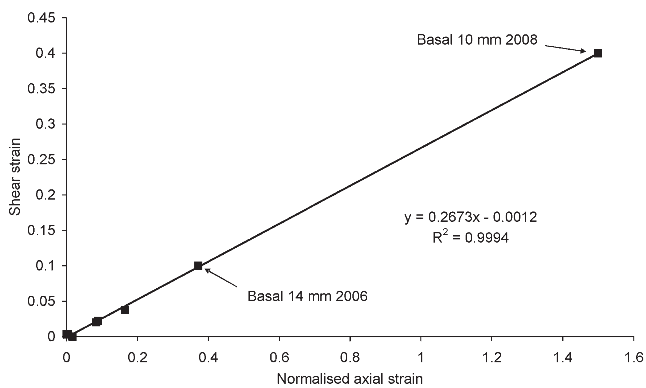

Figure 16 Plot of shear strain within successively thawing soil layers against normalised axial strain (thaw consolidation within the layer divided by unfrozen consolidated thickness of the layer) for the entire three-year period.

landsliding on low-level solifluction sheets in Svalbard similar to that at Endalen.

Influence of Seasonal and/or Annual Climate on Solifluction Processes and Rates

Although only spanning three years, the present study has highlighted the particular sensitivity of solifluction processes in Endalen to the depth of thaw penetration in summer. Basal soil deformation occurred only when summer thaw exceeded that of the previous year and the thaw front penetrated the ice-rich transient zone (2005–06 and 2007–08). The occurrence of basal shear strain in 2005–06 and 2007–08 significantly increased volumetric sediment transport rates (termed volumetric velocity by Matsuoka, 2001), with values of 162.6 cm^3/cm/yr in 2005–06 and 59.3 cm^3/cm/yr in 2007–08, compared to only 23.6 cm^3/cm/yr in 2006–07.

In 2006–07, the active layer was shallower than in the previous year, thawing did not penetrate the ice-rich basal zone and no basal shear strain was observed, solifluction being confined to the near surface. Although surface movement in 2006–07 was less than in the previous year (2.2 cm in 2005–06, 1.2 cm in 2006–07), it slightly exceeded that recorded in 2007–08 (1.0 cm). Basal shear strain giving plug-like active-layer movements in 2007–08 was therefore associated with a volumetric sediment transport rate more than double that recorded in 2006–07 despite surface displacements in 2007–08 being slightly less than in 2006–07. Thaw penetration depths in summer 2006 exceeded those in summer 2005 owing to elevated air temperatures, while cooler conditions in 2006–07 restricted summer active-layer thaw depths. In summer 2008, air temperatures were not exceptionally high, but ground temperatures were elevated by strong thermal insulation provided by the unusually thick early snow cover (in November, December and January) during the previous winter (see Figure 7 and 8).

CONCLUSIONS

The aim of this field study was to investigate the influence of interannual climatic variability on solifluction processes within a low-angled solifluction sheet, a landform that is widespread in Svalbard. The near-surface ground thermal regime and its influence on the depth of summer thaw penetration have been shown to play the major role in both the timing of soil movements, displacement profiles, and volumetric sediment transport rates. However, complex interrelationships between soil water migration, phase changes and soil thermal conditions have also been identified. The main conclusions drawn from the study are summarised below.

1. Significant interannual fluctuations in atmospheric temperatures were observed, with cumulative FDDs ranging from 775 FDDs in 2005–06 (October–September inclusive), to 1196 FDDs in 2006–07 and 1206 FDDs days in 2007–08. However, the ground thermal regime was strongly influenced by snow depth and duration. In 2007–08, the maximum snow depth at the monitoring station was 54 cm, lasting for a period of three weeks, compared with 47 cm, lasting only one day in 2005–06. As a result, ground surface temperatures in 2007–08 were higher than those in 2005–06, as was clearly illustrated by the cumulative FDDs of ground surface temperature which totalled only 263 in 2007–08, compared with 553 in 2005–06 and 831 in 2006–07.
2. The presence of an ice-rich transient zone at the base of the active layer, extending at least 1 m and probably significantly more into the underlying permafrost, played a major role in slow mass movement processes on the monitored slope only in summers when the thaw front penetrated this layer.
3. Autumn freeze-back of the active layer was associated with almost isothermal conditions persisting for several weeks during which active-layer temperatures were between 0°C and −0.2°C. During this time, ice segregation caused frost heaving of the ground surface, with recorded values of 4.2 cm in 2005–06, 6.6 cm in 2006–07 and 3.2 cm in 2007–08. Ice segregation was largely concentrated in the upper 40 cm of the active layer, with some segregation ice also forming in the lowermost 10 cm. The intervening mid-layer remained ice-poor. This indicates the importance of top-down one-sided active-layer freezing in the relatively warm permafrost of Svalbard (Christiansen *et al.*, 2010) compared with many other high arctic regions (Romanovsky *et al.*, 2010).
4. Immediately following the initiation of ground thawing in spring, the release of meltwater behind the advancing thaw front led to percolation downwards into still-frozen soil below. Refreezing of this percolating meltwater generated ice pressures and released latent heat, rapidly raising temperatures within the frozen soil in the ice-poor central zone of the active layer.
5. Recorded late-summer thaw depths were 106 cm in 2006, 100 cm in 2007 and close to 110 cm in 2008. In 2005, when instrumentation was installed, the active-layer depth was 94 cm, so that in late-summer 2006, thawing penetrated more than 10 cm into the ice-rich transient zone. In 2007, thawing did not reach the transient zone, but in late-summer 2008, a further 4 cm of basal ice-rich frozen soil were melted.
6. Thaw settlements recorded at the surface exceeded frost heave values in each year. The end of summer ground surface elevation was reduced by a total of 6.2 cm between 2005 and 2008, reflecting the thickness of ground ice lost over that period.
7. Following soil thawing at any given depth in the active layer, positive pore pressures were recorded, with pressure increasing with depth. Maximum recorded values at 90 cm were 11.4 kPa in August 2006, 10.3 kPa in August 2008, but only 3.9 kPa in August 2007, indicating artesian pressures in the basal active

layer in 2006 and 2008, but sub-hydrostatic pressures in 2007. Pore pressures at 90-cm depth were insufficient to cause rapid slope failure (active-layer detachment landslides) in 2006, but slope stability analysis predicted that an increase of only 14 per cent would have been sufficient to bring this slope to the threshold for shallow translational landsliding.

8. Downslope movement at the surface was recorded only during active thaw settlement and appeared to be controlled by it. Total downslope displacement amounted to 2.2 cm in summer 2006, 1.2 cm in summer 2007 and 1.0 cm in summer 2008. In 2006 and 2008, downslope movements occurred in early summer as near-surface layers thawed, and again in late summer as the basal ice-rich layer thawed. In contrast, in 2007, when active layer thawing failed to reach the basal transient zone, solifluction was largely restricted to the early summer period when the uppermost 40 cm of soil thawed.
9. Although surface movement rates were slightly less in 2008 than 2007, the occurrence of basal shear strain in 2008 led to soil volumetric transport rates more than double those in 2007 when no basal shear strain occurred. In 2006, surface movement was high, significant basal shearing also occurred and volumetric transport was nearly seven times higher than in 2007. These results are consistent with laboratory simulation studies at full-scale (Harris *et al.*, 2008a, b) and reduced scale (Kern-Leutsch *et al.*, 2008), which showed volumetric transport rates between two and three times higher for a given surface displacement on slopes with basal shearing (plug-like movements), compared with those where solifluction shear strains decreased with depth and no basal shearing occurred.
10. Utilising the real-time thermal, thaw settlement and downslope displacement data collected here, a comparison was possible between axial strain (thaw settlement divided by unfrozen thickness) within successive soil layers and shear strain within those layers. A very strong positive linear relationship was found, with shear strain directly related to axial strain (thaw settlement). This relationship was similar to that observed in laboratory simulation studies by Harris *et al.* (2008a, b) and Kern-Luetschg *et al.* (2008), though the coefficient was lower here for the Svalbard soils than was the case for the silt loam test soils used in the modelling experiments.
11. A trend towards higher atmospheric temperatures and deeper active layers in Svalbard associated with climatic changes would likely lead to a rapid increase in sediment transport rates due to solifluction, with the possibility of shallow landsliding on low-angled solifluction sheets during extreme warm years. However, future trends in snow depth and duration, which are yet to be established, are likely to strongly modulate the atmospheric temperature signal in respect to the near-surface ground thermal regime and related mass movement processes on Svalbard slopes.

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